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Abstract

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Prolonged physical exercise tests (50 min) at the threshold of 4 mmol·l^{-1} lactate (AT_C) and at the individual anaerobic threshold (IAT) were applied in 19 rowing athletes. In each of the rowers (n = 19) work loads corresponding to the IAT did not result in a gradual lactate accumulation or exhaustion within 60 min of exercise. Means of lactate concentration and heart rate at the end of exercise were 4.0 ± 1.6 mmol·l^{-1} and 182 ± 13.0 beats·min^{-1}, respectively. In 15 of 19 rowers, the IAT corresponded to lower work loads than the AT_C. In these cases, prolonged exercise tests at the AT_C showed gradual increases in lactate concentrations to a mean of 9.6 ± 1.2 mmol·l^{-1}, associated with exhaustion at a mean working time of 14.4 ± 6.3 min and a mean heart rate of 192 ± 10.4 beats·min^{-1}. In four rowers, the IAT was found at identical (n = 3) or higher (n = 1) work loads than the AT_C. In these cases, after an initial increase no further rise in lactate concentrations in blood was observed, and exhaustion did not occur during the prolonged exercise tests. These findings support the conclusion derived from the lactate kinetics model that the IAT defines the work load at the maximal lactate steady state.

Key words: Individual anaerobic threshold, fixed anaerobic threshold, prolonged exercise test, lactate

Introduction

Prolonged physical exercise is generally performed at a fractional utilization of maximal aerobic capacity ($\dot{V}O_2max$) only (2, 17, 5, 14). Experimental evidence derived from long-distance running performance (2) and laboratory tests (14) indicates little or no lactate accumulation in blood at work loads up to 80% of $\dot{V}O_2max$. A slight increase in running speed above a critical limit has been reported to result in a rapid increase in lactate concentration in blood (2). The work load corresponding to $\dot{V}O_2max$ is always associated with high lactate accumulation. The highest possible work load without a gradual increase in lactate in blood seems to be a better predictor of the level of conditioning in endurance performance diagnostics than $\dot{V}O_2max$ (5, 14, 17, 18). This steady state of lactate is reached when lactate production and lactate uptake are equal (2, 14).

Recently, various concepts for determination of this work load have been presented using either parameters of gas exchange (26, 27, 10), parameters of lactate metabolism (13, 14, 17–19, 22), or both (5). Some of these concepts are derived from lactate concentrations in blood. However, lactate concentrations in blood will only give tentative information about true lactate production, as considerable differences exist between lactate concentrations in blood and muscle during exercise (11, 12, 16). Some of the concepts are either based on fixed lactate concentrations in blood (14, 17, 18) or fixed inclinations of lactate concentrations (17, 22). They do not take into account individual lactate kinetics (19, 23–25). Lactate kinetics in blood during and immediately after stepwise increasing exercise to exhaustion is based on diffusion along gradients (4, 11, 12, 16) and simultaneous elimination (3, 6, 20, 28). By a new model derived from these basics (23–25), the individual anaerobic threshold (IAT) was defined as the work load corresponding to the steady state between diffusion of lactate into the blood compartment and maximal elimination from the blood and muscle compartments. In contrast to fixed concentration and inclination concepts, the IAT was located at individually different concentrations of lactate in blood and at individually different inclinations of the blood lactate curve. In prolonged exercise, work loads corresponding to the IAT led to a steady-state lactate concentration in blood (23). In a considerable number of cases, the work loads at the IAT inevitably differ from those at fixed concentration or inclination values. This paper deals with prolonged exercise at work loads corresponding to the IAT and the 4 mmol·l^{-1} threshold. The purpose of this investigation was to elicit from 50-min exercise tests whether a steady state in lactate metabolism can be attained at both thresholds.

Material and Methods

Some descriptive characteristics of nine male and ten female rowers who volunteered as subjects are shown in Table 1.

Exercise with stepwise increasing loads until the point of exhaustion was performed by each rower on an electrically braked bicycle ergometer in a sitting position as fol-

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Tab. 1 Descriptive characteristics of nine male and ten female rowing athletes (means ± SD)

Group	n	Age (years)	Height (cm)	Weight (kg)	Heart size (ml)	Heart size ($ml \cdot kg^{-1}$)	$\dot{V}O_2max$ ($ml \cdot min^{-1}$)	$\dot{V}O_2max$ ($ml \cdot min^{-1} \cdot kg^{-1}$)
Male	9	17.1 ± 1.6	182.2 ± 6.5	76.9 ± 6.5	931 ± 129	12.1 ± 1.3	4297 ± 334	58.0 ± 5.7
Female	10	18.5 ± 2.5	173.4 ± 2.1	67.2 ± 4.9	698 ± 83	10.3 ± 0.8	3581 ± 164	53.4 ± 3.3

lows: each subject started at 50 W (♀) or 100 W (♂) with 50 W being added every 2 min. Oxygen uptake was measured continuously with an open system at the end of each work load; heart rate was determined from the electrocardiogram. Arterialized blood for enzymatic determination (9) of the lactate concentration was taken with heparinized glass capillaries from the hyperemic earlobe at rest, at the end of each work load, and several times during the initial 15 min of the post-exercise period. The IAT was determined by the model formerly described in detail (24). By means of linear interpolation, the AT_c was assessed from blood lactate concentrations in progressive exercise tests to 4 $mmol \cdot l^{-1}$ (14, 15, 18). From the curvilinear increase in lactate concentrations in blood, the inclinations at the IAT and the AT_c were assessed by means of respective tangents (Fig. 5), the dimensions being: $mmol \cdot l^{-1} \cdot min^{-1}$ [The increase in work load has been standardized (15) and therefore is a function of working time]. Fixed inclination thresholds (AT_i) (13, 22) have been determined to be at an angle of either 51° or 45° from the base line level, corresponding to inclinations of either 1.26 $mmol \cdot l^{-1} \cdot min^{-1}$ or 1.0 $mmol \cdot l^{-1} \cdot min^{-1}$, respectively. Inclinations given in angular degrees depend on the scaling of the x and y axis, and inclinations given in correct dimensions do not. However, for comparison purposes in this paper, inclinations are given in angular degrees using the same scaling as the above authors. Slope differences at the IAT and the AT_c were assessed by $\sphericalangle \alpha$ according to Fig. 5.

Prolonged exercise tests of 50 min duration were carried out in each subject at the work loads determined by the IAT and the AT_c. Every 5 min, blood was taken from the hyperemic earlobe for determination of lactate concentration. Work was continued during blood sampling. Heart rate was taken every 5 min. Perceived exertion was rated by the Borg scale (1) at the end of each test. Work was stopped after 50 min or earlier if exhaustion occurred.

Linear regression analysis performed for working time to exhaustion in prolonged exercise tests versus the inclination of the blood lactate curve at the AT_c was compared to working time to exhaustion versus the angle between the inclinations at the IAT and the AT_c ($\sphericalangle \alpha$).

All values reported are means ± SD. Values were looked upon as significant at $P < 0.05$.

Results

The subjects could be divided into three groups according to the relationship between the AT_c and the IAT.

Group I

In 15 of 19 rowers, work loads and blood lactate concentrations in the stepwise exercise tests were found to be lower at the IAT than at the AT_c (Table 2). In this group all the rowers worked for 50 min at the IAT, but none were able to work for this time at the AT_c. At work loads corresponding to the IAT after an initial increase arterial lactate concentrations stabilized at individually different levels; in contrast, lactate concentrations increased continuously in the tests at the AT_c (Figs. 1 and 2). The

Tab. 2 Work loads, blood lactate concentrations, and heart rates as obtained from progressive exercise tests to exhaustion compared to values obtained from prol. exercise at the IAT and AT_c (means ± SD). Subjects are grouped according to the relationship between the IAT and the AT_c, as assessed in the progressive exercise tests

		Progressive exercise test							IAT-prol. exercise (last interval)				AT_c-prol. exercise (last interval)			
Group	n	max. values			IAT		AT_c									
		Work load (Watt)	Lactate ($mmol \cdot l^{-1}$)	HR (min^{-1})	Work load (Watt)	Lactate ($mmol \cdot l^{-1}$)	Work load (Watt)	Lactate ($mmol \cdot l^{-1}$)	Lactate ($mmol \cdot l^{-1}$)	HR (min^{-1})	Duration (min)	Borg scale (No)	Lactate ($mmol \cdot l^{-1}$)	HR (min^{-1})	Duration (min)	Borg scale (No)
I								IAT < AT_c								
a) ♂	7	340.0 ±28.9	10.0 ±1.6	195.0 ± 6.0	212.1 ±29.2	2.4 ±0.4	266.4 ±25.8	4.0	3.1 ±0.9	177.3 ±17.1	50	13.7 ±3.3	9.4 ±1.2	193.7 ± 8.7	16.6 ±4.0	18.0 ±0.9
b) ♀	8	280.0 ±16.7	9.8 ±1.8	193.7 ± 6.9	174.7 ±17.3	2.3 ±0.3	221.4 ±15.6	4.0	4.3 ±1.4	184.2 ± 9.1	50	14.2 ±2.4	9.7 ±1.0	191.0 ±11.9	12.4 ±7.0	18.0 ±1.2
Total	15	308.0 ±35.9	9.9 ±1.6	194.3 ± 6.3	192.7 ±20.7	2.3 ±0.36	242.0 ±30.1	4.0	3.75 ±1.34	181.0 ±13.2	50	14.0 ±2.7	9.6 ±1.2	192.1 ±10.4	14.4 ±6.3	18.0 ±1.1
II								IAT = AT_c								
	3	333.3 ±57.7	13.5 ±0.8	194.2 ± 9.8	191.7 ±17.6	4.0 ±0.2	191.7 ±17.6	4.0	4.5 ±0.4	177.0 ±15.6	50	11.7 ±3.2	4.5 ±0.4	177.0 ±15.6	50	11.7 ±3.2
III								IAT > AT_c								
	1	375	18.9	189	235	6.1	175.0	4.0	8.8	191	50	16.0	2.6	146	50	11

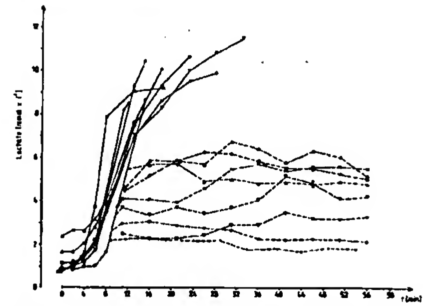

Fig. 1 Lactate concentrations in prolonged exercise tests in seven male rowers (group I)
work load at the IAT (— — — —), work load at the AT_c (———)

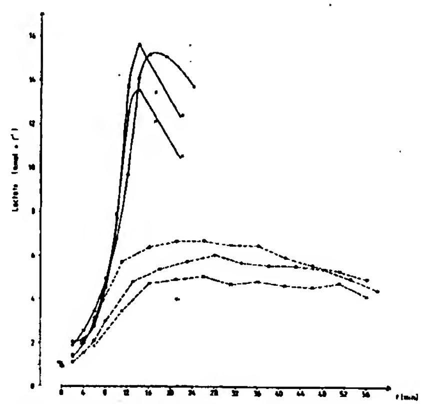

Fig. 3 Lactate concentrations in three rowers (group II) in prol. exercise at the IAT = AT_c (— — — —)
progressive exercise test (———)

lactate levels at exhaustion were similar to those at the end of the stepwise exercise tests (Table 2).

Group II

In three rowers, work loads and lactate concentrations at the IAT and the AT_c were identical (Table 2). At these work loads, exercise could be sustained for 50 min, and lactate concentrations reached a steady state (Fig. 3).

Group III

In one rower, work load and lactate concentration at the IAT was distinctly higher than at the AT_c (Table 2). In this case, the work at the IAT was tolerated for 50 min

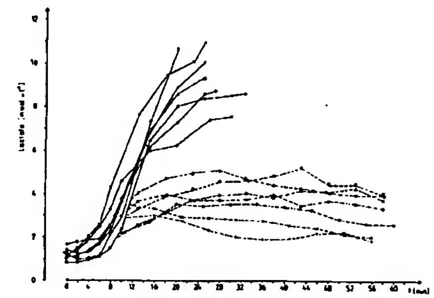

Fig. 2 Lactate concentrations in prolonged exercise tests in eight female rowers (group I)
work load at the IAT (— — — —), work load at the AT_c (———)

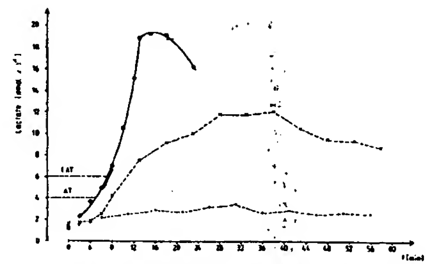

Fig. 4 Lactate concentrations in one rower (group III) in prol. exercise at the IAT (x— — —x), prol. exercise at the AT_c (+— — —+), progressive exercise test (———)

without exhaustion, with the arterial lactate initially increasing considerably and then decreasing to a constant level. The lower work load at the AT_c could also be continued for 50 min (Fig. 4).

The mean heart rate and the mean rate of perceived exertion as assessed by the Borg scale after 50 min exercise at the IAT, and after different working times at the AT_c as calculated from each group, are given in Table 2.

VO_2max as obtained from stepwise tests and %VO_2max at the IAT and the AT_c are given in Table 3. The means and standard deviations of inclinations at the AT_c and the IAT and means of working times in consecutive endurance tests are listed in Table 4.

With the 15 subjects in group I, the prolonged exercise tests at the AT_c led to early exhaustion in 50-min exercise tests and was associated with lactate acidosis. In these tests, the time to exhaustion was plotted against the respective inclination of the blood lactate curve in the stepwise exercise test at the AT_c. The results of the linear regression analysis are given in Table 5. The regression coef-

Tab. 3 Maximal oxygen uptake ($\dot{V}O_2$max) and percentage of $\dot{V}O_2$max uptake at the IAT and the AT_c (means ± SD, range)

Group	n	$\dot{V}O_2$max (ml)	IAT %$\dot{V}O_2$max	AT_c %$\dot{V}O_2$max
I a) ♂	7	4189 ± 278 (3790 – 4650)	66.8 ± 7.3 (55 – 77)	81.0 ± 4.6 (74 – 87)
b) ♀	8	3545 ± 159 (3235 – 3750)	64.2 ± 3.5 (57 – 69)	82.1 ± 4.4 (73 – 88)
II	3	4114 ± 637 (3740 – 4850)	61.0 ± 5.0 (56 – 66)	61.0 ± 5.0 (56 – 66)
III	1	4500	68	50
I + II + III	19	3920 ± 441 (3235 – 4850)	64.8 ± 5.4 (55 – 77)	77.0 ± 10.7 (50 – 88)

ficient was negative, as expected. The correlation between variables was poor and, 0 hypothesis could be rejected in the "total rowers" group only on a 5% probability basis.

In the 15 subjects of group I, the difference between the slope at the AT_c and the slope at the IAT was assessed according to Fig. 5 by the $\sphericalangle\,\alpha$. This was plotted against working time to exhaustion in prolonged exercise tests at the AT_c. The results of the linear regression analysis are given in Table 6: The regression coefficient was negative, as expected. The correlation between the variables was high in all groups, thus 0 hypothesis could be rejected on a high probability basis. The 95% confidence limits for the regression lines were calculated according to (21)

Tab. 4 Slopes at the IAT and AT_c, slope differences as assessed by $\sphericalangle\,\alpha$, and working time in endurance tests (means ± SD, range)

Group	n	Progressive exercise test			Prol. exercise-working time (min)	
		IAT (range)	AT_c (range)	$\sphericalangle\,\alpha$ (range)	AT_c (range)	IAT
I a) ♂	7	26°±6° (20°–35°)	46°±4° (40°–53°)	20°±6° (14°–31°)	16.6±4 (10–22.5)	50
b) ♀	8	32°±6° (20°–38°)	54°±5° (47°–61°)	22°±8° (15°–34°)	12.4±7 (5–25)	50
Total	15	29°±7° (20°–38°)	50°±6° (40°–61°)	21°±7° (14°–34°)	14.4±6 (5–25)	50
II	3	40°±4° (36°–41°)	40°±4° (36°–41°)	0°	50	50
III	1	62°	32°	(-20°)	50	50
I + II + III	19	31°±9° (20°–62°)	48°±7° (32°–61°)			

Tab. 5 Data obtained from linear regression analysis of working time until exhaustion (group I) vs slope at the AT_c

Group	n	Regression coeff.	Correlation coeff.	Syx	P
Male	7	- 0.248	- 0.260	3.6	NS
Female	8	- 1.018	- 0.650	5.1	NS
Total rowers	15	- 0.631	- 0.599	4.7	< 0.05

Tab. 6 Data obtained from linear regression analysis of working time until exhaustion (group I) vs $\sphericalangle\,\alpha$

Group	n	Regression coeff.	Correlation coeff.	Syx	P
Male	7	- 0.63	- 0.929	1.36	< 0.01
Female	8	- 0.76	- 0.869	3.29	< 0.01
Total rowers	15	- 0.75	- 0.840	3.18	< 0.001

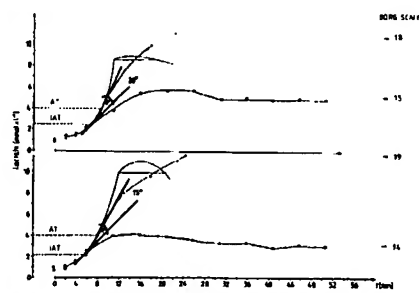

Fig. 5 Determination of the difference between the slope at the IAT and the AT_c in the blood lactate curve obtained from progressive exercise test ($\sphericalangle\,\alpha$) in two female rowers: prolonged exercise at the IAT (•——•), prolonged exercise at the AT_c (+——), progressive exercise test (———)

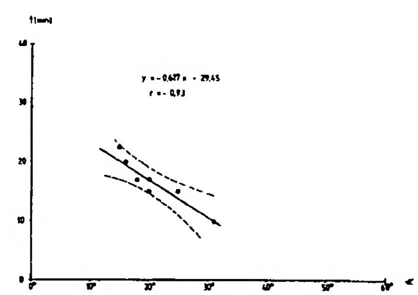

Fig. 6 Linear regression analysis of working time until exhaustion vs $\sphericalangle\,\alpha$ and 95% confidence limits of the regression line in the males of group I

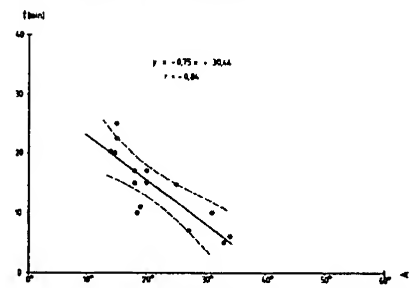

Fig. 7 Linear regression analysis of working time until exhaustion vs ∢ α and 95% confidence limits of the regression line in "all rowers" of group I

$\hat{Y} \pm \sqrt{2F_{2,(n-2)}} \cdot Syx$ in the "male group" (Fig. 6) and also in the "total rowers" group (Fig. 7).

No regression analysis was made if ∢ α = 0°, as all of the rowers worked for 50 min at this condition without physical signs of exhaustion.

Discussion

In this investigation, a larger number of cases showed lower work loads at the IAT compared to the 4 mmol·l⁻¹ threshold. In not especially endurance-trained athletes, i.e., physical education students, the mean lactate concentration at the IAT has been found to be 4.6 mmol·l⁻¹ lactate (23–25). In this group of physical education students, prolonged exercise tests (50 min) corresponding to the IAT displayed a steady state in lactate concentrations; however, in 8 of 12 students the IAT was > 4 mmol·l⁻¹ threshold (23). It therefore can be concluded that in cases in which the IAT was found to be above or below the AT_c, work loads corresponding to the maximal lactate steady state had been either under- or overestimated at the AT_c as the respective prolonged exercise tests indicated.

The means of the inclinations of the lactate curve at the AT_c in group I (Table 4) is in close agreement with the values given earlier for the increment at the AT_i of 45° (22) and 51° (13), although in prolonged exercise tests, exhaustion occurred on an average after 16.6 min and 14.4 min, respectively (Table 4).

Prolonged exercise at work loads above the AT_i is expected to result in progressive lactate acidosis. The higher the inclination, the shorter the working time. Thus, the working time in prolonged exercise tests can be expected to be closely correlated to the inclinations obtained from progressive exercise tests at the AT_c in group I. In each case, this working time to exhaustion was tested by regression analysis versus the absolute inclination of the lactate curve at the AT_c, and by ∢ α (Tables 5 and 6). The correlation coefficients of -0.599 versus -0.840 indicate that working time to exhaustion is more tightly coupled to ∢ α than to inclinations at the AT_c. In further support of these findings was the much smaller standard error of estimate (Syx) found for working time versus ∢ α compared to working time versus the inclinations at the AT_c. The significantly lower correlation coefficient for working time versus the inclination at the AT_c suggests that this relationship does not approximate a linear model as well as working time versus ∢ α does. A feature noteworthy in this respect is that regression of working time on ∢ α yields a positive intercept estimate at ∢ α = 0° on the time axis at approximately 30 min. As has been shown by experiment in all tested rowers (n = 19), exercise would have been tolerated for more than 50 min at ∢ α = 0° (IAT). Thus, a linear model for working time (group I) versus ∢ α can only be accepted if 10° < ∢ α < 40°. Further investigations beyond these limits will probably reveal a regression curve of hyperbolic shape. However, 95% confidence limits of the total regression line indicate that prediction of working time to exhaustion in prolonged exercise tests at work loads above the IAT seems to be possible within acceptable limits (Figs. 6 and 7).

It can be concluded that working time to exhaustion associated with gradual lactate accumulation in prolonged exercise tests is tightly coupled to the ∢ α obtained from stepwise exercise tests. Given that ∢ α = 0 represents the IAT, the theoretical argument coupled with our findings in prolonged exercise tests at the IAT is consistent with the hypothesis that the IAT identifies the maximal lactate steady state. Indirect evidence for this assumption can be drawn from the fact that if $AT_c \neq$ IAT then $AT_c \neq$ maximal lactate steady state in respective prolonged exercise tests. These experimental results are in good agreement with the definition of the IAT in the lactate kinetics model (24).

The higher the aerobic power in athletes, the more the maximal lactate steady state will be overestimated if determined at 4 mmol·l⁻¹ lactate (13, 23–25). The aerobic power of the examined rowers was distinctly above the average. Therefore, mean lactate concentration at the IAT was expected to be lower than 4 mmol·l⁻¹ as could be confirmed by this investigation (Table 2). Earlier investigations indicating an inverse relationship of $\dot{V}O_2$max and the mean lactate level at the IAT have shown that lactate concentrations within groups of similar $\dot{V}O_2$max vary within broad limits (18, 19, 20). This is in accordance with lactate concentrations at the IAT ranging from 1.8–6.1 mmol·l⁻¹ in this investigation.

Oxygen uptake (Table 3) was 64.8 ± 5.4% of $\dot{V}O_2$max at the IAT, ranging individually from 55%–77%. These values correspond well with other experimental data concerning the onset of lactate accumulation during bicycle exercise (11, 12, 16).

As far as physical conditioning in athletic events is concerned, the knowledge of the individual maximal lactate steady state becomes more important the longer a certain work load has to be sustained. This is especially the case in long events. Here the IAT will be a valuable indicator of individual fitness. In contrast to the IAT, the ∢ α may turn out to be a valuable indicator in the assessment of athletic competence at work loads exceeding the maximal lactate steady state.

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